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Procedia Engineering 160 (2016) 21 – 28

**Procedia
Engineering**www.elsevier.com/locate/procedia

XVIII International Colloquium on Mechanical Fatigue of Metals (ICMFM XVIII)

Some influencing variables on internal fatigue crack initiation in structural materials

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Abstract

Major variables which cause internal fatigue crack initiation are nonmetallic inclusions in high strength steels, surface roughness and notch in structural components and corrosive environments. This paper focused on the effect of stress concentration factor and corrosive environment for internal fatigue crack initiation of structural materials mainly based upon author's experimental results. In the results of conventional and ultrasonic fatigue testing on notched specimens with stress concentration factor of 1.5, 2.0 and 2.5 for 0.65 mass % carbon matrix high speed steel with HRC 60.7, subsurface fatigue crack initiation was observed on all notched specimens at failed number of cycles over than 10^6 . On the contrary fatigue crack initiated from notched specimen surface for powdered high speed steel with HRC 67 with stress concentration factor of 2.0. The fatigue crack initiation mode in notched specimens at high cycle region may be governed by surface hardness of high speed steels.

The different effect of corrosive environment on fatigue crack initiation is demonstrated in the plate bending fatigue testing results of 1% carbon steel and 13Cr-1Mo steel in refrigeration compressor gaseous environment. For 1% carbon steel fatigue crack initiated from subsurface at lower fatigue life of 5×10^6 cycles, while fatigue crack initiated from surface corrosion pit at higher fatigue life of 5×10^6 cycles. For 13Cr-1Mo steel subsurface fatigue crack initiation was predominantly observed in air and in refrigeration compressor gaseous environment.

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Peer-review under responsibility of the University of Oviedo

Keywords: Subsurface fatigue crack initiation, Notch, Stress concentration factor, High speed steel, Corrosive environment, 1% Carbon steel, 13Cr-1Mo steel

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1.Introduction

So far it has been well recognized that the ratio of fatigue limit to ultimate tensile strength is about 0.5 in case of steels with ultimate tensile strength of 1200MPa. At levels of tensile strength greater than the fatigue limit tends to flatten off, or at least increase more slowly. The reason is related to the fact that fatigue crack is easier to initiate at very high strength level. In case of high strength steels cracks tend to initiate at surface or inclusions located at subsurface rather than surface slip in lower strength steels [1]. It has been well documented now that the sudden reduction of fatigue strength of high strength steel in very high cycle region is due to the internal fatigue crack initiation at nonmetallic inclusions. Many examples of subsurface fatigue crack initiation at nonmetallic inclusions have been reported in very high number of cycles [2]. Giga-cycle fatigue behavior for various kinds of metallic material has also been reported in related to subsurface crack initiation [3].

Investigation on internal fatigue crack initiation is absolutely important not only to estimate long term fatigue strength for fatigue design stress but also to clarify fatigue crack initiation mechanism. However, most of the papers on internal fatigue crack initiation have been reported on high cycle fatigue testing results of plane specimens in air. The most of the components of machine and structures have some irregularities and notches, however there are very few papers on long term fatigue testing data for notched specimens.

In this paper the emphasis is placed upon the effect of stress concentration factor on subsurface fatigue crack initiation for high strength steels. Corrosive environmental effect on subsurface crack initiation is also demonstrated in plate bending fatigue testing results of 1% carbon steel and 13Cr-1Mo steel under refrigeration compressor gaseous environment.

2.Effect of stress concentration factor on subsurface fatigue crack initiation for high strength steels

Automotive forging dies most frequently fail from the short fatigue crack initiated at the impression corner during forging operations[4]. Therefore it is necessary to clarify the fatigue and fracture behavior of forging die steels in order to prevent forging die failure and to improve forging die life. However not so many information has been reported on fatigue and fracture behavior of cold forging die steels with high hardness. Author has been so far investigated on fatigue and fracture behavior of cold forging die steels with Rockwell C scale number of 60 to 67 [5,6,7,8,9]. High cycle fatigue tests were conducted on YXR3 cold forging die steel[7]. The used material is representative cold forging die steel of 0.65mass% carbon matrix high speed steel. In vacuum this steel was austenitized 1123K for 2.25h, 1293K for 0.42h, 1408K for 0.42h, oil quenched and tempered at 813K for 2h, at 813K for 2.25hr, at 838K for 1.67hr and air cooled. Ultimate tensile strength and Rockwell C scale hardness number of YXR3 steel is 2192MPa and 60.0 HRC, respectively. The plane round bar specimens with 6.5 mm at minimum diameter and notched round bar specimens with stress concentration factor, K_t of 1.5, 2.0 and 2.5 were used (Fig.1). Stress concentration factor determined by use of Neuber monograph[10] is shown in Table 1. Surface roughness was measured by use of contact probe profilometer. Ten-point mean surface roughness R_z of the as-lapped plane bar specimen was $0.25 \pm 0.36 \mu\text{m}$. Load controlled fatigue tests were conducted by use of a hydraulic fatigue testing machine at room temperature. Frequency was 20Hz and R (the ratio of minimum to maximum stress in the loading cycle) value was 0.05. The S-N diagrams of plane and notched specimens of YXR3 steel in high cycle region is shown in Fig.3. The fatigue strength and fatigue life of the notched specimens were decreased as compared with those of plane bar specimen. Fatigue limit at 10^7 cycles of the notched specimens with stress concentration factor of 1.5, 2.0 and 2.5 were 350, 250 and 175 MPa, respectively. The fatigue limit decrease at 10^7 cycles of the notched specimen with stress concentration factor of 1.5, 2.0 and 2.5 was 12.5, 37.5 and 56.3 %, respectively.

In Fig.3 the S-N curves on low cycle fatigue strength of notched specimen with various stress concentration factor for YXR3 steel [6] is also shown. As same as the high cycle fatigue strength the lower the stress concentration factor the higher the low cycle fatigue strength is. Ultrasonic fatigue tests were also conducted on YXR3 steel used for high cycle fatigue[9]. The notched round bar specimens with stress concentration factor, K_t of 1.5, 2.0 and 2.5 were used as shown in Fig.2. The dimensions of notched radius R, notched length ℓ and stress concentration factor K_t are shown in Table.2. Surface roughness was measured by use of contact probe profilometer. Ten-point mean surface roughness R_z of the notch depth for $K_t=1.5, 2.0$ and 2.5 were 0.349, 1.031 and $0.782 \mu\text{m}$, respectively. Ultrasonic fatigue tests were conducted by use of a laboratory made ultrasonic fatigue testing machine at room temperature.

Frequency was 20kHz and R (the ratio of minimum to maximum stress in the loading cycle) value was -1 . The ultrasonic fatigue testing results for notched specimens of YXR3 are shown in Fig.3. Fatigue limit at 10^9 cycles for the notched specimens with $K_t=1.5$, 2.0 and 2.5 were 700,650 and 400MPa, respectively. The higher the stress concentration factor the smaller the fatigue limit at 10^9 cycles was. This inclination was as same as those of low cycle and high cycle fatigue testing results of YXR3 steel [6,7]. The higher fatigue strength in ultrasonic fatigue test than that in high cycle fatigue test is attributed to the frequency effect. High cycle fatigue fracture surfaces were observed by scanning electron microscopy. In plane bar specimen crack initiated at subsurface as observed on low cycle fatigue fracture surfaces[6]. On the contrary crack initiation site was changed from notched surface to subsurface at failed number of cycles over than 10^6 for all notched specimens with stress concentration factor, K_t of 2.0 and 2.5. Fig.4 a),b) show the difference of crack initiation site in notched bar specimen with stress concentration factor of 2.0. The subsurface crack initiated at carbides. Thus it can be emphasized that the subsurface crack can be

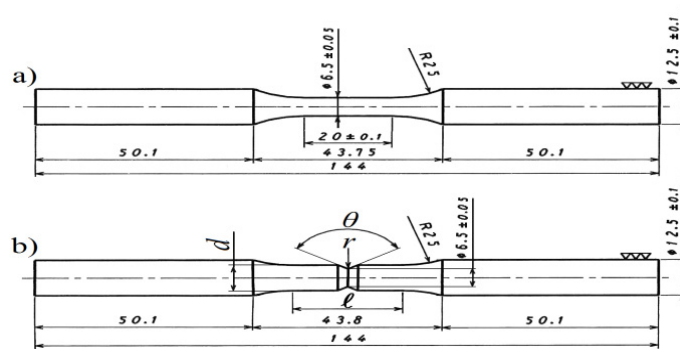


Fig.1 High cycle fatigue test specimen.
a)plane specimen b) notched specimen

Table1 Stress concentration factor of notched specimen.

r(mm)	d(mm)	ℓ(mm)	θ (degree)	K_t
0.5	6.66	20.3	120	1.5
1.0	8.20	23.5	60	2.0
0.5	8.76	24.8	60	2.5

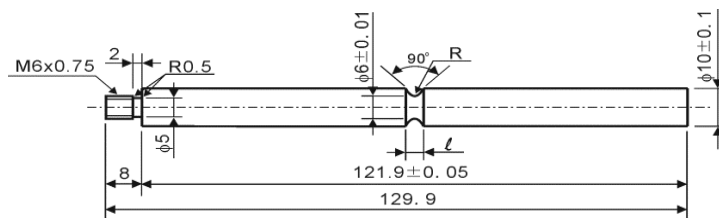


Fig.2 Ultrasonic fatigue test specimen.

Table2 Stress concentration factor of notched specimen.

R(mm)	ℓ(mm)	K_t
4 ± 0.05	7.31	1.5
1.6 ± 0.05	5.33	2.0
0.8 ± 0.05	4.66	2.5

observed in high cycle range over than 10^6 cycles even for the notched specimen in YXR3 steel with high ultimate tensile strength of 2192 MPa. Transgranular fracture surfaces were predominant (Fig.4c,d)) and well defined striation were not observed in crack propagation area for all tested specimens. In the

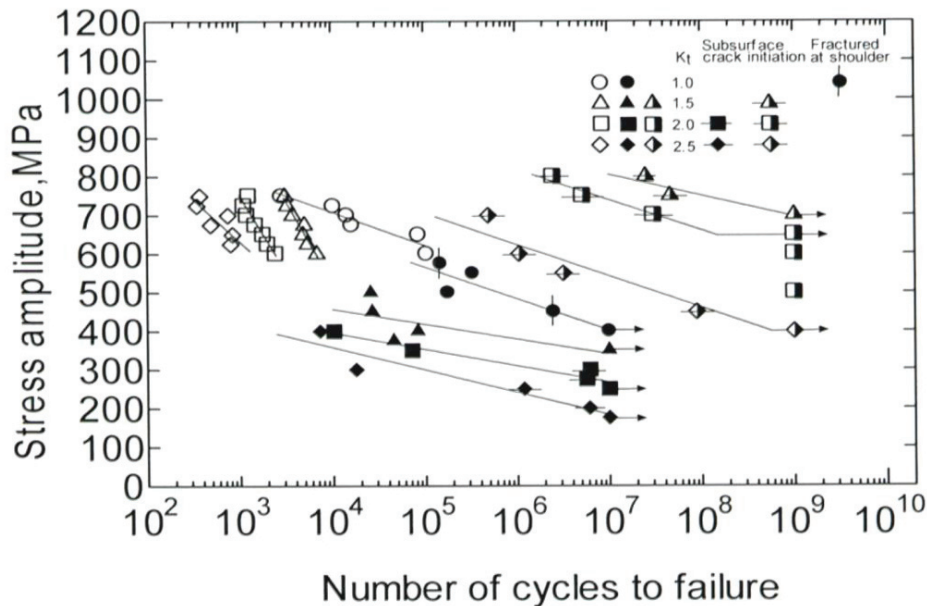


Fig.3 S-N diagrams of plane and notched specimens of YXR3 steel.

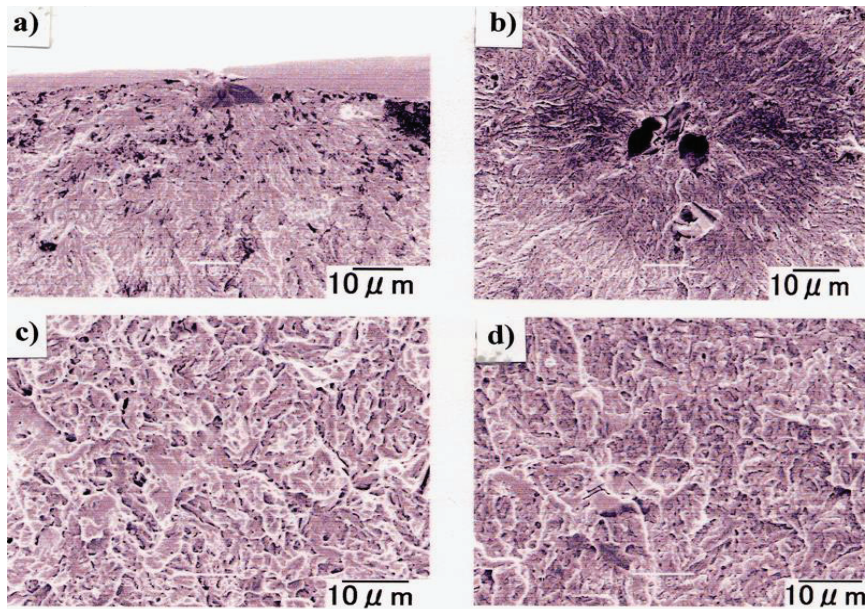


Fig.4 High cycle fatigue fracture surface of YXR3 with $K_t=2.0$.

- a),b) crack initiation area
- c) 0.8mm from initiation, d) 0.6mm from initiation
- a),c) 400MPa, 1×10^4 cycles, b),d) 300MPa, 6.2×10^6 cycles

ultrasonic fatigue fracture surfaces it was observed that fatigue crack did not initiate at notched surface and initiated at nonmetallic inclusions located at subsurface for all notched specimens. It is well recognized that the subsurface crack initiation is most frequently observed for high strength plane specimens failed at higher number of cycles. In fact the subsurface crack initiation from nonmetallic inclusions were observed on plane specimen for YXR3 with HRC60.5 and SKH51 steel with HRC60.5 in very high cycle ranges [5]. In low cycle fatigue fracture surface observations crack initiated from surface at lower than 8×10^4 cycles for plane specimen, while crack initiated from notched surface for notched specimen. Thus for YXR3 steel it can be concluded that for plane specimen subsurface crack initiation from nonmetallic inclusions at high cycle higher than 8×10^4 to giga-cycle region, while crack initiation site for notched specimen shifts from notched surface to subsurface after about 10^6 cycles up to giga-cycle region. Author also has conducted ultrasonic fatigue test for powdered high speed steel [8]. Commercial HAP72 was

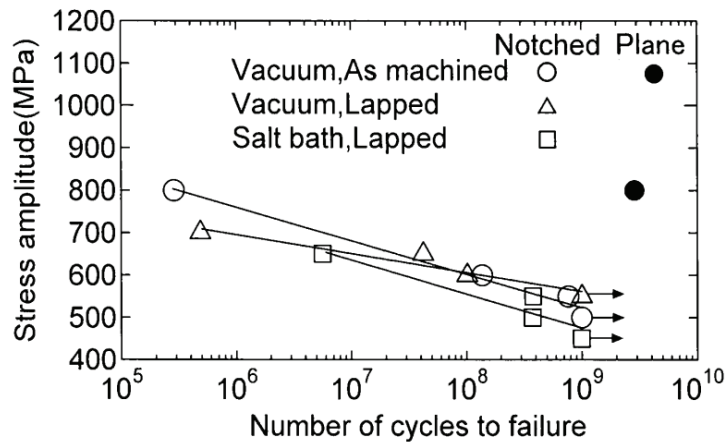


Fig.5 S-N diagrams for HAP72.

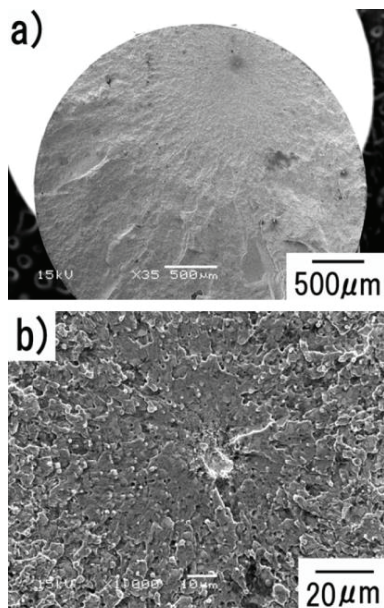


Fig.6 Fatigue fracture surface of plane specimen.
HAP72, as machined, 800MPa, 2.8×10^9
a) macroscopic fracture surface
b) crack initiation area

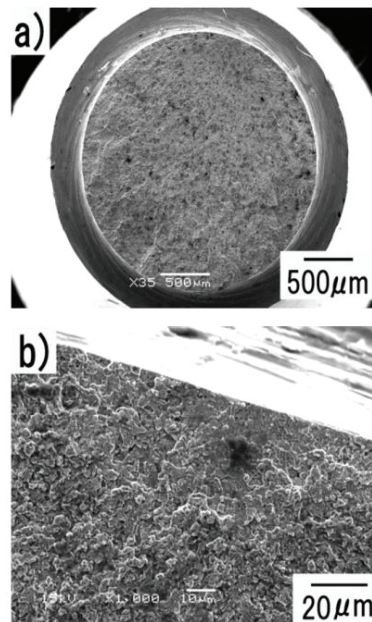


Fig.7 Fatigue fracture surface of notched specimen.
HAP72, as machined, 800MPa, 2.8×10^5
a) macroscopic fracture surface
b) crack initiation area

selected. The chemical compositions in mass% consisted of 2.08C, 0.4Si, 0.27Mn, 0.018P, 0.008S, 4.23Cr, 9.6W, 8.15Mo, 4.95V and 9.63Co. This steel was heat treated in vacuum and in salt bath. In vacuum the steel was austenitized at 1123K for 2.25hr, 1293K for 0.42hr, 1433K for 0.05hr, oil quenched and triple tempered at 823K for 1.5hr, air cooled. In salt bath the steel was austenitized at 973K for 0.5hr, 1103K for 0.33hr and 1453K for 0.5hr, oil quenched and triple tempered at 823K for 1.5hr and air cooled. Ultimate tensile strength and Rockwell C scale hardness number was 1804MPa and HRC67, respectively. Surface roughness was measured by use of a contact probe profilometer R_z was $1.3 \mu\text{m}$ for as-machined specimen and $0.1 \mu\text{m}$ for as-lapped specimen. For ultrasonic fatigue tests dumbbell type round bar specimens with minimum diameter of 3mm and total length of 69.2mm was used. The circular notch was formed at the minimum diameter of 3mm. The stress concentration factor of the notched specimen was 2.0. Fatigue life of the notched specimen decreased to 0.01% that of the plane specimen tested at 800MPa as shown in Fig.5. For plane specimen fatigue crack initiated from non-metallic inclusion such as Fe-W, V, Mo located at subsurface as shown in Fig.6, while fatigue crack initiated at notched surface for all tested notched specimens as shown in Fig.7. The ultrasonic fatigue testing results of high strength SUJ2 steel with HRC63.3 was also reported on fatigue crack initiation in notched specimens [11]. In this experiment fatigue crack initiation from non-metallic inclusion located at subsurface was observed in plane and notched specimen with stress concentration factor with 1.8, while fatigue crack initiated from surface in notched specimens with stress concentration factor with 2.7 and 3.9. The different crack initiation mode in notched specimen of high strength steels may be deeply related to surface hardness, fracture toughness, notch sensitivity and stress gradient. Further investigation on fatigue crack initiation of notched specimen in high strength steels is expected to conduct. The information on fatigue crack initiation in long term used actual components with and without notch is desired to disclose.

3. Effect of corrosive environment on subsurface crack initiation of high strength steel

Fatigue testing results on refrigeration compressor valve steels have been reported so far [12,13,14,15]. However very few papers have been reported on environmental effect on fatigue strength of compressor valve steels. Plate bending fatigue tests on refrigeration compressor valve steels such as 1% carbon steel and 13Cr-1Mo steel were conducted in air and in refrigeration compressor gaseous environment [16]. Chemical compositions and mechanical properties of tested steels are shown in Table3 and Table4, respectively. Fatigue tests were conducted by use of the laboratory made corrosion fatigue testing apparatus which composed of refrigerant circulation apparatus, testing chamber and plate bending fatigue testing machine (0.5Ton). Testing environment was a simulated refrigerant environment such as SUNISO3GS (refrigerant oil) containing R12 (99.8% freon gas) with 0.98MPa at 120°C. Plate

Table3 Chemical compositions of tested materials (mass%).

Material	C	Si	Mn	P	S	Cr	Mo
1% C steel	0.95	0.22	0.22	0.013	0.015		
13Cr-1Mo	0.36	0.68	0.46	0.016	0.003	13.3	0.88

Table4 Mechanical properties of tested materials.

Material	0.2%Proof stress	Ultimate tensile strength	Elongation	Hardness
	MPa	MPa	%	HV
1%C Steel	1574	1812	6.6	534
13Cr-1Mo	1557	1857	2.9	606

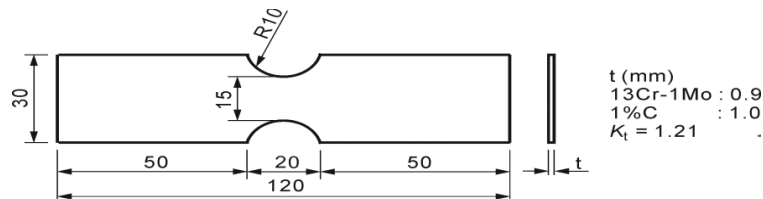


Fig.8 Fatigue test specimen.

specimen as shown in Fig.7 was used. Fatigue test was conducted by use of laboratory made plate bending fatigue testing apparatus. Stress wave form was sinusoidal. Frequency was 13.3Hz and R value was 0.05. S-N diagrams of 1%C steel and 13 Cr-1Mo steel in air and in refrigeration compressor gaseous environment is shown in Fig.9. For 1%C steel fatigue strength in air is lower than that in (R12+SUNISO3GS) environment at number of cycles lower than 5×10^6 , while fatigue strength in air is higher than that in environment at number of cycles higher than 5×10^6 . At number of cycles lower than 5×10^6 the (R12+SUNISO3GS) environment in the testing chamber is kept as an inert environment after vacuum drawing up to 10^{-3} torr. Therefore fatigue strength in (R12+SUNISO3GS) environment is higher than that in air. At number of cycles higher than 5×10^6 , the separated H_2O and Cl by decomposition of R12 deteriorate SUNISO3GS. Therefore, the (R12+SUNISO3GS) environment in the testing chamber turns to corrosive environment from inert environment. SEM observations revealed that subsurface fatigue crack initiation was observed at number of cycles lower than 5×10^6 . On the other hand fatigue crack initiation from corrosion pit formed at surface was observed at number of cycles higher than 5×10^6 . The different fatigue crack initiation mode is demonstrated in Fig.10. In case of 13Cr-1Mo steel fatigue strength in (R12+SUNISO3GS) environment is higher than that in air up to 10^7 cycles. From this fact it can be mentioned that corrosion resistance of 13Cr-1Mo steel in (R12+SUNISO3GS) environment is higher than that in 1%C steel. However, corrosion fatigue is a time dependent phenomenon. It is necessary to watch long term fatigue behaviour of 13Cr-1Mo steel in (R12+SUNISO3GS) environment. For 13Cr-1Mo steel fatigue crack initiated from non-metallic inclusion or intercrystalline both in air and in (R12+SUNISO3GS) environment. The examples of subsurface crack initiation from non-metallic inclusion

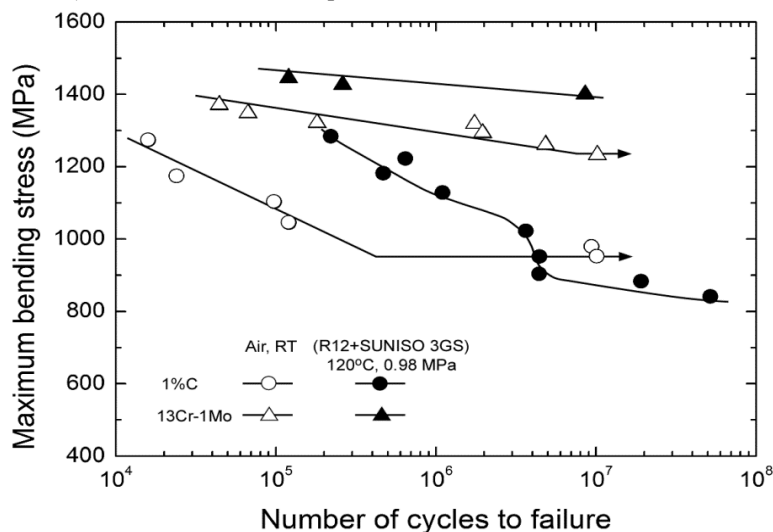


Fig.9 S-N diagrams of 1%C steel and 13Cr-1Mo steel in air and in (R12+SUNISO3GS) environment.

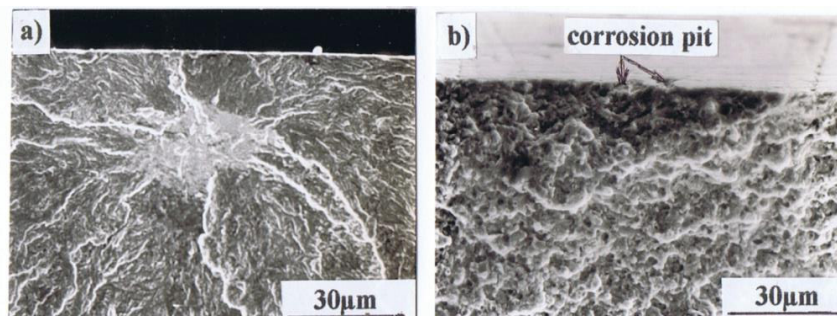


Fig.10 Subsurface fatigue crack initiation of 1% C steel in (R12+SUNISO3GS) environment.

a) 956 MPa, 4.2×10^6 cycles

b) 842 MPa, 5.1×10^7 cycles

and intercrystalline in air are shown in Fig.11. It can be concluded that corrosion pit formed at surface is one of the influencing variables on internal fatigue crack initiation at subsurface crack initiation.

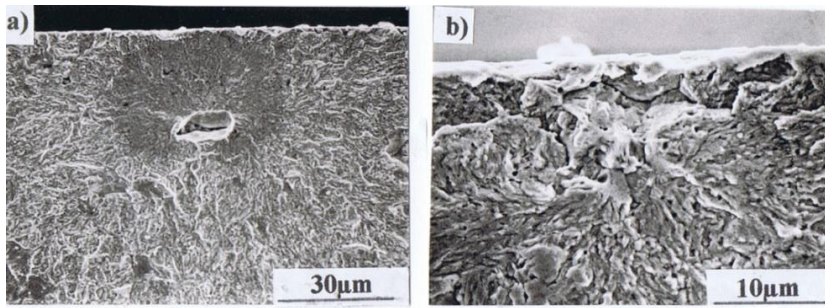


Fig.11 Subsurface fatigue crack initiation of 13Cr-1Mo steel in air.

a)1323MPa,1.8x10⁶cycles

b)1265MPa,4.7x10⁶cycles

4. Concluding remarks

A brief survey was conducted on the effect of stress concentration factor and corrosive environment on internal fatigue crack initiation of high strength structural materials mainly based upon author's experimental results.. Fatigue crack initiation from the notched surface was observed on HAP72 with K_t of 2.0 and SUJ2 with K_t higher than 2.7 and 3.9. However, subsurface crack initiation was observed on YXR3 with K_t of 1.5 to 2.5 and SUJ2 with K_t of 1.8. To understand the subsurface fatigue crack initiation for notched specimen at high cycle region the further studies are necessary to conduct on the stress gradient of the notched portion and notch sensitivity of structural steels. Information from case studies for subsurface fatigue crack initiation from notch in actual components is also desired to disclose. Subsurface crack initiation of structural materials is deeply related to corrosion pit initiation in corrosive environment. Further studies are expected on corrosion pit initiation mechanism and quantitative analysis on corrosion fatigue crack initiation of structural materials.

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